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Six-Tube Freezable Radiator Testing and Model Correlation

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Freezable Radiators offer an attractive solution to the issue of thermal control system scalability. As thermal environments change, a freezable radiator will effectively scale the total heat rejection it is capable of as a function of the thermal environment and flow rate through the radiator. Scalable thermal control systems are a critical technology for spacecraft that will endure missions with widely varying thermal requirements. These changing requirements are a result of the spacecraft's surroundings and because of different thermal loads rejected during different mission phases.

However, freezing and thawing (recovering) a freezable radiator is a process that has historically proven very difficult to predict through modeling, resulting in highly inaccurate predictions of recovery time. These predictions are a critical step in gaining the capability to quickly design and produce optimized freezable radiators for a range of mission requirements. This paper builds upon previous efforts made to correlate a Thermal Desktop™ model with empirical testing data from two test articles, with additional model modifications and empirical data from a sub-component radiator for a full scale design. Two working fluids were tested: MultiTherm WB-58 and a 50-50 mixture of DI water and Amsoil ANT.

I. INTRODUCTION

SPACECRAFT designed for missions outside of low lunar orbit provide a different challenge to the thermal control system, primarily from the varying thermal environments experienced throughout any given mission, and also from varying thermal requirements. Particularly in the case of crewed spacecraft, the thermal system must be able to maintain a nearly uniform temperature inside the cabin despite these varying loads and environments. For example, examine Figure 1. The red line represents the heat that needs to be rejected from the spacecraft during different mission phases, while the blue line represents the sink temperature of the radiators as it changes from one environment to the next. Examining the Trans Lunar Coast (TLC) and Lunar Surface Operations (LSO) phases, we can see that the thermal system is required to reject first relatively little heat into a relatively cool environment, then it is required to reject about six times as much heat into a much warmer environment. If the heat rejection components of the thermal control system are designed to handle LSO, they will be underutilized in TLC, causing them to get very cold. The spacecraft's thermal system must find a way to still do its job during LSO, but be able to survive TLC without freezing solid.

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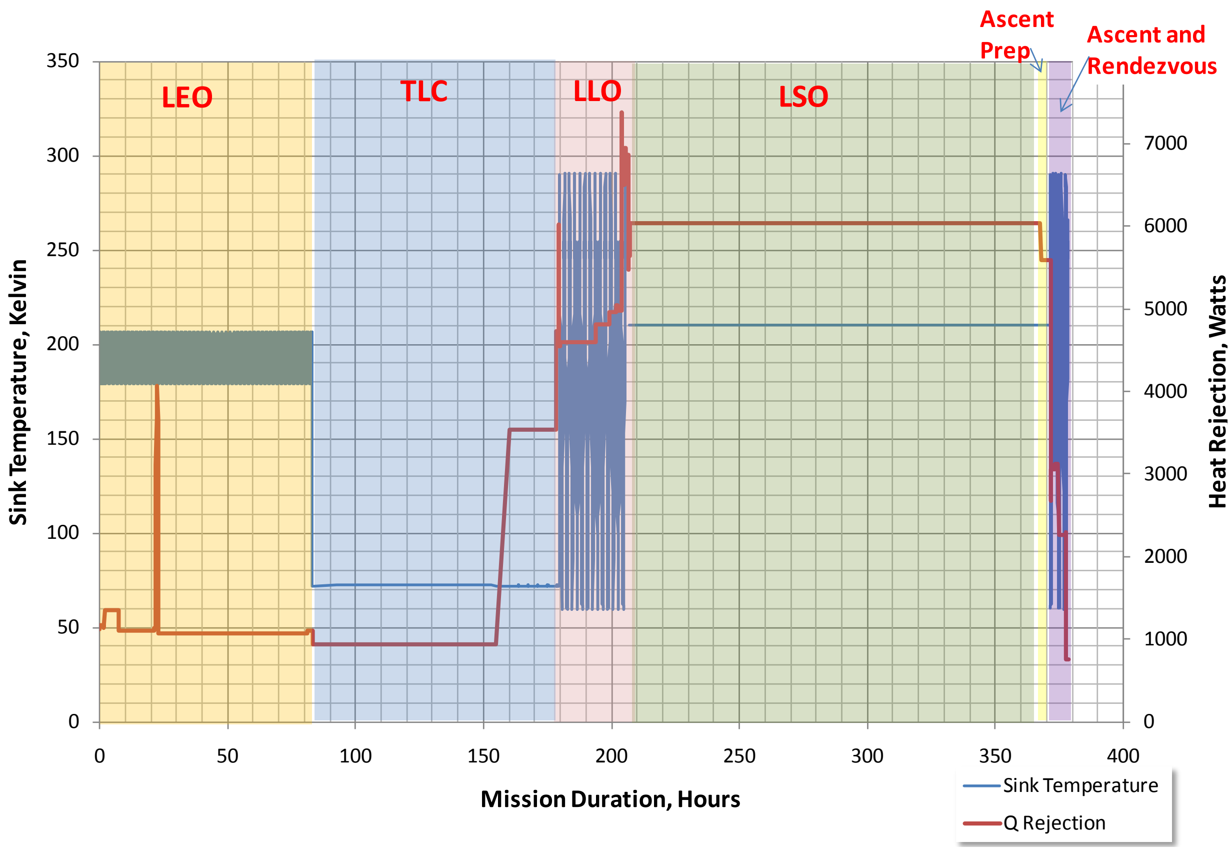

Figure 1: Representative thermal profile for a lunar mission. Mission phases are listed: Low Earth Orbit (LEO), Trans-Lunar Coast (TLC), Low Lunar Orbit (LLO), Lunar Surface Operations (LSO), Ascent Preparation, and Ascent and Rendezvous.

Traditionally, the solution to this problem for crewed spacecraft has been to use one of two options. The first is a single fluid loop with a low-freeze temperature fluid. However, there are no known fluids that have a sufficiently low freeze temperature that are also human-friendly, which is important in the case of a leak of thermal control fluid into the cabin. The second traditional option is a dual-fluid loop, where two separate loops are used, one with a human-friendly fluid for cabin use, and one with a low-freeze temperature fluid for use through the radiators and other cold components. This second option requires additional hardware (twice the pumps, an interface heat exchanger, etc.) and more power, but is safer for the crew.

The purpose of a freezable radiator is to give us the advantage of the single fluid loop with none of the drawbacks: to allow for a simple, reliable, lightweight single fluid loop that can use human friendly fluids. Because of their relatively high freeze temperatures, this means that during the colder parts of the mission (like TLC in Figure 1) the radiator will need to be able to handle fluid freezing in its tubes and to actively recover those tubes later when it needs them to reject a higher heat load.

II. OBJECTIVE

The development of a radiator that freezes its tubes in a predictable manner is a relatively simple fluid problem, however, accurate prediction of the recovery behavior (and other transient behavior) has proven difficult. A model has been developed and refined with the purpose of accurately synthesizing the bulk behavior of a freezable radiator. The primary objective of this test is to confirm changes that have been made to the current model used to predict freezable radiator performance, and to provide additional data that allows further model improvements to have empirical data for comparison.

The secondary objective of this test is to evaluate the performance of the test article geometry as a freezable radiator. This is quantified by evaluating maximal heat rejection, minimal heat rejection, and the ratio between the two, which is called turn-down ratio. The evaluation of the performance of this radiator in particular has importance because the test article geometry is very similar to a sub-component of a full scale freezable radiator designed to accomplish the 6:1 turndown ratio shown in Figure 1.

III. TESTING EQUIPMENT

Test Article

The test article for this test has been fabricated by Paragon SDC. What follows will describe the dimensions and rationale for that test article. Fabrication processes will not be discussed in order to protect Paragon trade secrets.

The test article represents an approximation of one quarter of a full scale design. This sub-component test article's radiating surface measures 16.25 inches (41.28 cm) in width and 96.00 inches (244 cm) in length and has six tubes running parallel along the panel length. The test article radiating surface is coated with Aeroglaze Z306, which has an emissivity of approximately 0.88. Images 1 and 2 show the test article used.

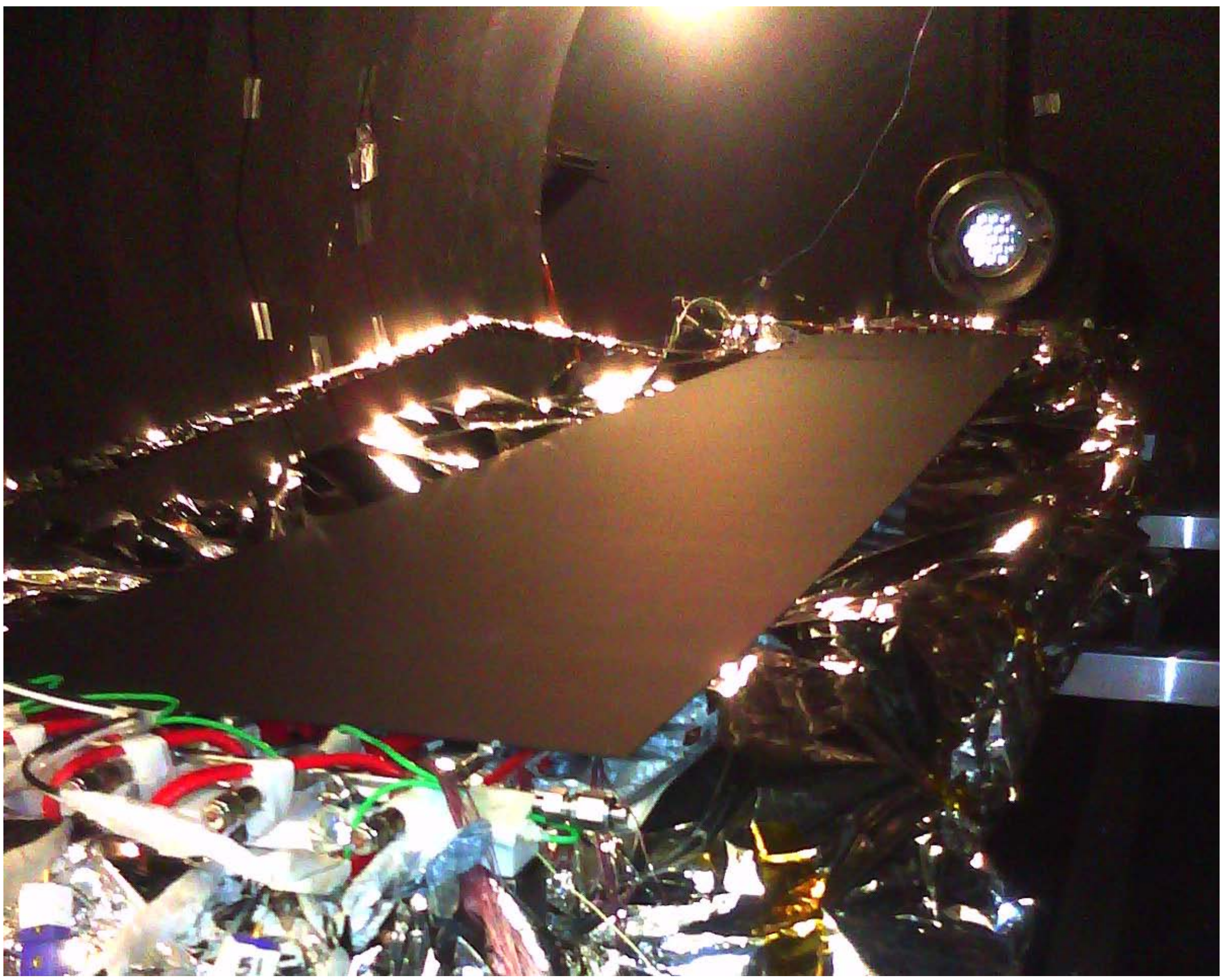

Image 1: Freezable radiator shown in testing configuration in Chamber E. The black rectangle in the center of the image is the test article radiating surface, surrounded by layers of Mylar insulation.

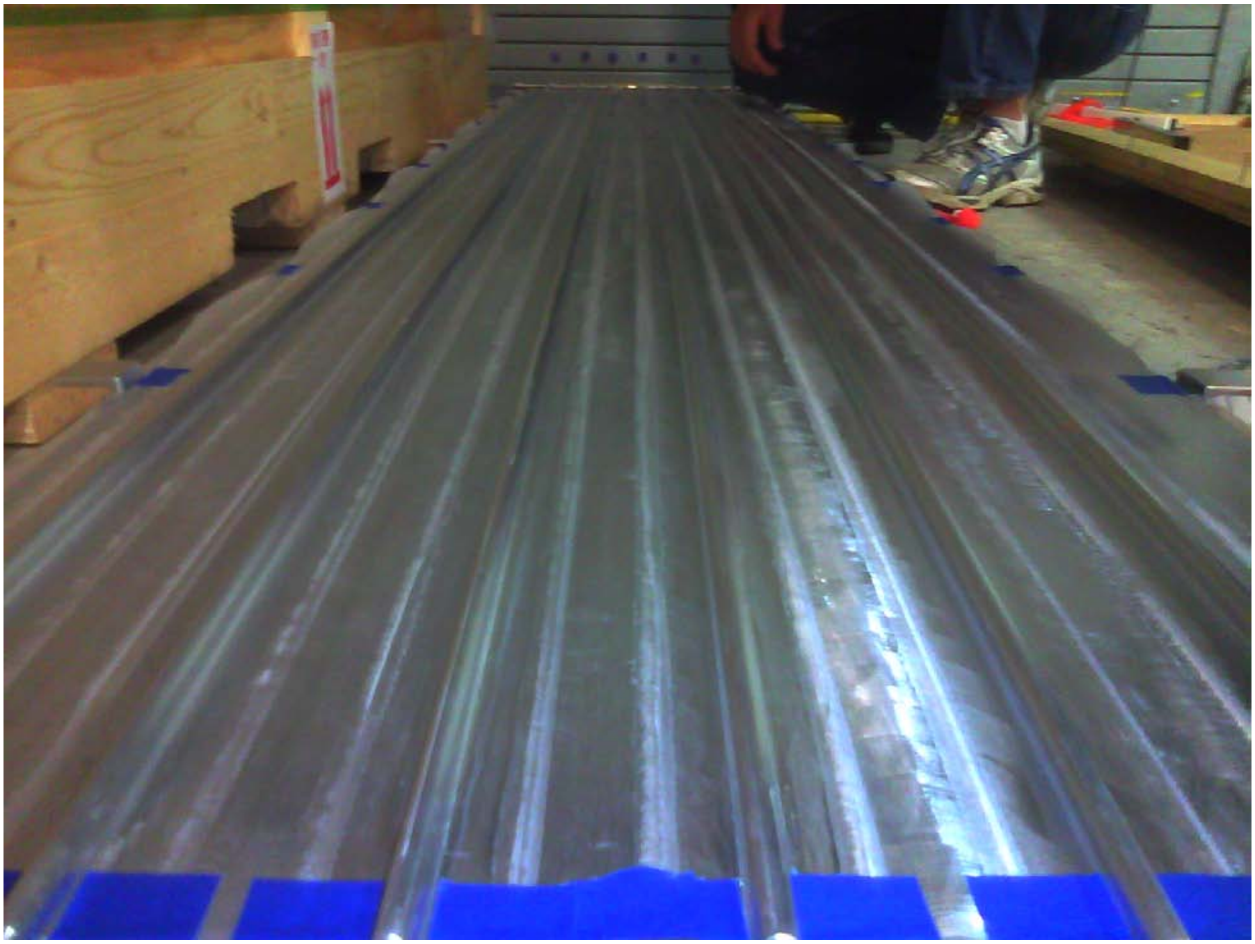

Image 2: Freezable radiator test article underside shown looking down the length of the test article. Six parallel tubes run from foreground to background in the image.

The flow through the radiator tubes is parallel, with the inlet and outlet manifold coming from the same side of the radiator (making a C-shape path, illustrated in Figure 2). This tube layout allows for incrementally more flow friction through each tube from the tube closest to the fluid inlet to the tube farthest from the inlet. As a result of this increased flow friction, slower flow is seen on each successive tube from the one nearest to the inlet to the one farthest from the inlet of the manifold. Slower flow beneath the radiator results in colder fluid temperatures for that flow path, so the fluid coming out of the radiator would always be coldest in the sixth tube and warmest in the first tube. This means that the sixth tube was always the first to stagnate and freeze, and that the first tube was always the last to freeze (optimally it should not freeze at all).

Testing Fluids

Two fluids are tested in this test article. MultiTherm WB-58, a water-based fluid with a proprietary ionic compound, was primarily tested for performance and evaluation of the radiator. Amsoil ANT and DI H_2O in a 50/50 solution by mass is tested for performance comparison and for continuity with previous tests which also used a propylene glycol-water solution. Prior to this test, a survey of currently produced thermal fluids was conducted when modeling results began to predict that no feasible design result could be found allowing for a turn-down ratio of 6:1 or greater. The two fluids tested here were the most promising yielded from that fluids study, according to preliminary modeling results.

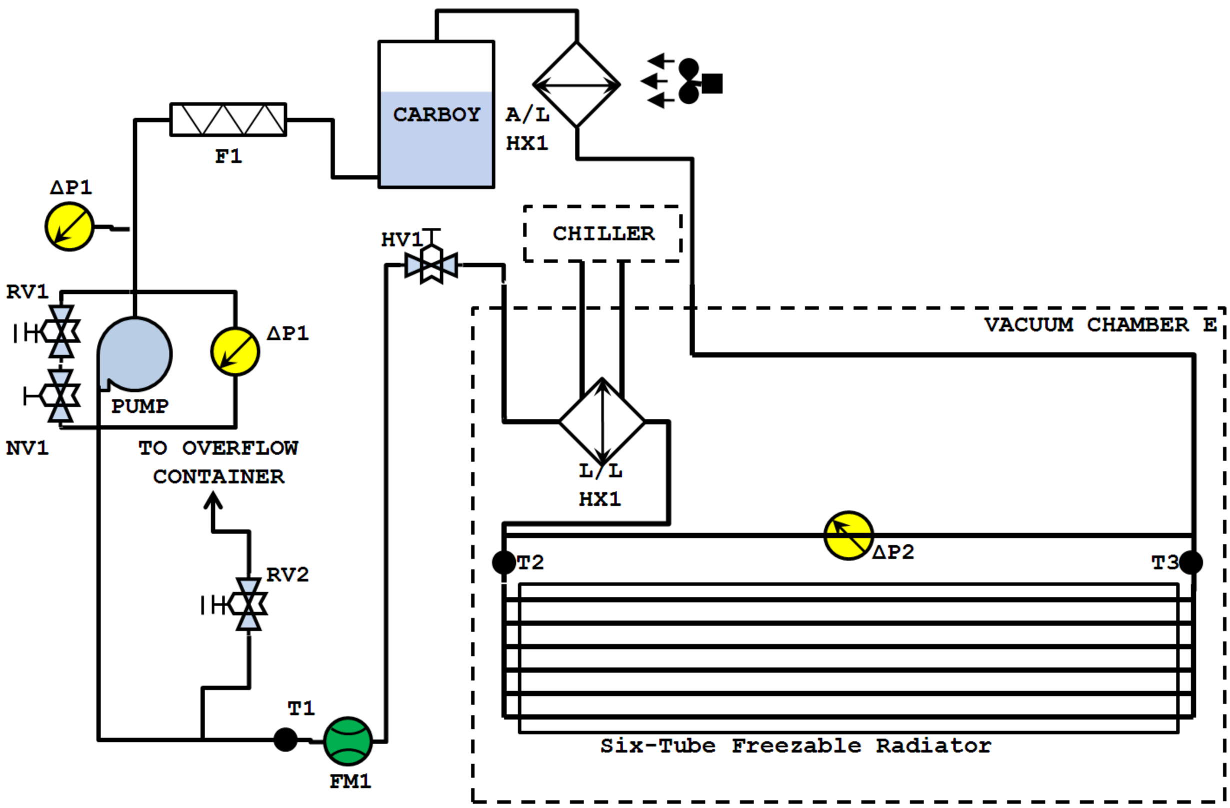

Figure 2: Schematic of the test stand.

Test Stand

The test stand itself is shown in Figure 2. Starting at the pump, the fluid travels through the flow meter, then into the vacuum chamber. After entering the vacuum chamber the fluid is conditioned to the desired inlet temperature by way of the liquid-liquid heat exchanger. This is done in the chamber because the flow rates used during testing are very low, and thus the test fluid lines are susceptible to fluid temperature change when passing near or through objects of different temperature to the fluid (namely, the ambient environment and the wall of the vacuum chamber). After being conditioned to the desired inlet conditions, the fluid flows through the test article and returns out of the vacuum chamber and through an air-liquid heat exchanger that helps bring the fluid back up to room temperature. Bringing the fluid back up to room temperature is done to help relieve stress on the pump internals, as room temperature fluid has much lower viscosities than the cold (sometimes nearly frozen) fluid coming out of the radiator. From here the fluid continues to the carboy and filter, thus completing the loop back to the pump.

Instrumentation

Instrumentation consists of the following:

- 16 thermocouple probes to measure the fluid temperature,
- 47 surface thermocouples placed primarily on the underside of the test article (one row of surface thermocouples was placed on the radiating surface),
- Two delta-pressure transducers, one measuring across the test article and one across the pump
- One absolute pressure sensor to evaluate pressure in the fluid line between the carboy and the pump
- One mass flow meter measuring total flow through the fluid loop

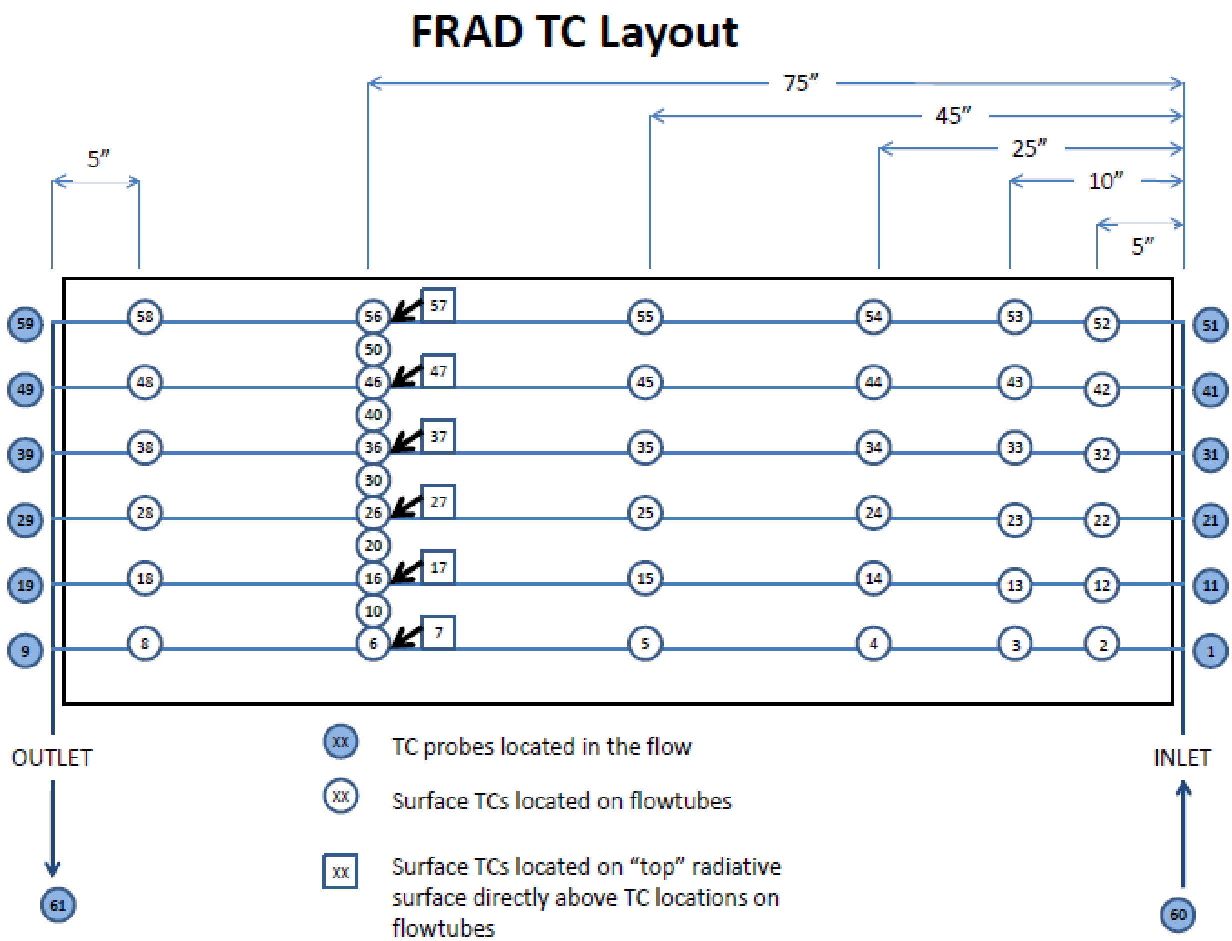

Figure 3: Thermocouple probe layout and numbering.

Figure 3 shows the thermocouple layout in detail on the test article, as well as the numbers of the thermocouple probes used to discern one from another during testing. The data presented in this quick-look report primarily concerns the last row of surface thermocouple probes before the test article outlet, namely thermocouples 8, 18, 28, 38, 48, and 58. These show a good characterization of what is going on in the tube. Because the tube walls are constructed of very thin aluminum, the temperature measured by these probes is very close to the temperature of the fluid near the wall of the tube. Because of fluid conductivity this may be different than the bulk temperature of the fluid, but nonetheless it gives a good initial indicator of performance to compare model results. The last row of thermocouples is chosen over any other row of thermocouples because the lowest temperatures are seen at these points for each tube. Thus, if a tube is going to freeze or stagnate, it will happen close to these thermocouples before it happens anywhere else in the tube.

The pressure transducers are primarily for indication during testing, as they display increases in pressure as the radiator reaches the lower limits of flow.

The mass flow meter is instrumental in determining radiator performance as it provides data required to quantify radiator behavior and heat rejection.

IV. TESTING

Testing Rationale

The battery of test points run for this test article serve the primary function of capturing the behavior of the test article at the extremes with regard to flow. Full tube flow is evaluated, and single tube flow is systematically determined and evaluated. Previous testing with propylene glycol showed that the time spent at single tube flow had an effect on recovery rate and behavior, so freeze dwell time is also evaluated.

The evaluation of the performance of the freezable radiator is the secondary function of this test. This is quantified by the energy rejected during full flow, the energy rejected during single-tube flow, and the ratio between these two energy rejections. The ratio between maximal and minimal energy rejection is referred to as turn-down ratio.

Prior model evaluations have shown that it is critical to know the properties of the fluids being used in a freezable radiator to a high degree of accuracy in order to accurately predict the test article behavior. The fluid test performed prior to this thermal vacuum test provides the data required for the fluids' conductivity, specific heat, density, and most importantly, viscosity.

Test Points

Test points were done in an order designed to maximize the use of test time. Maximal heat rejection is tested first at 31 lb/hr and a 20 C inlet temperature, followed by an incremental decrease in flow rate designed to determine what the minimal flow rate (the flow rate at which single-tube flow is achieved) of the test article-fluid pair is. With this determined, recovery is attempted by increasing flow back to full flow (31 lb/hr). After full flow has been achieved, the flow rate is again reduced, this time directly to the minimum flow rate found from the first freeze process, followed again by another recovery. With this complete, flow rate is dropped and held at the minimum flow to check for any effects stemming from long dwell time at cold temperatures. Dwell time was not evaluated for Amsoil ANT since its role in the test is only to provide continuity with previous tests. Primary correlation efforts will move forward with MultiTherm WB-58 as the modeled working fluid.

V. RESULTS

The results discussed below are representative of the test points seen during testing. Several iterations of freezing and thawing were run to test for repeatability. What is shown here is representative of all the test points seen during testing.

MultiTherm WB-58

Figure 4 shows cycle from full flow to single tube flow, followed by a direct return to full flow. The dashed lines represent empirical data, while the solid lines represent simulated data from the model receiving the same inputs as the test article. The data shown are from the last row of surface thermocouples, which are 8, 18, 28, 38, 48, and 58, shown in Figure 3. As can be seen, the model predicts a slightly slower and more delayed than the empirical data. Steady state temperatures are a few degrees warmer empirically than they are modeled.

Recovery displays interesting phenomena in the empirical data. Figure 4 again shows the exit temperature of tube 1 which is shown "notching" as it approaches its steady state temperature. These individual notches indicate each frozen tube recovering. As the tube warms, the frozen fluid inside reaches a temperature at which the slug of frozen fluid is no longer adhered to the inner tube wall enough to stay in place, and is thus flushed from the tube. This sudden increase in the number of flow paths results in a lower net flow in the already flowing tubes, which in turn momentarily decreases the temperature of the flowing tubes. The temperature "notch" seen in Figure 4 is caused by this phenomenon. The radiator model over-predicts the recovery rate of the radiator by approximately 30 minutes.

Maximal and minimal heat rejection was found by quantifying the removal of heat from the fluid based on mass flow, fluid properties, and temperature difference. This is subsequently verified by an area weighted average temperature of the radiator surface, used to calculate a simple black body radiation equation. Maximal heat rejection was found to be 282 Watts at 31 lb/hr and 20 °C inlet temperature. Minimal heat rejection was found at 4.8 lb/hr to be 108 Watts (same inlet temperature), making a turn-down ratio of 2.6:1.

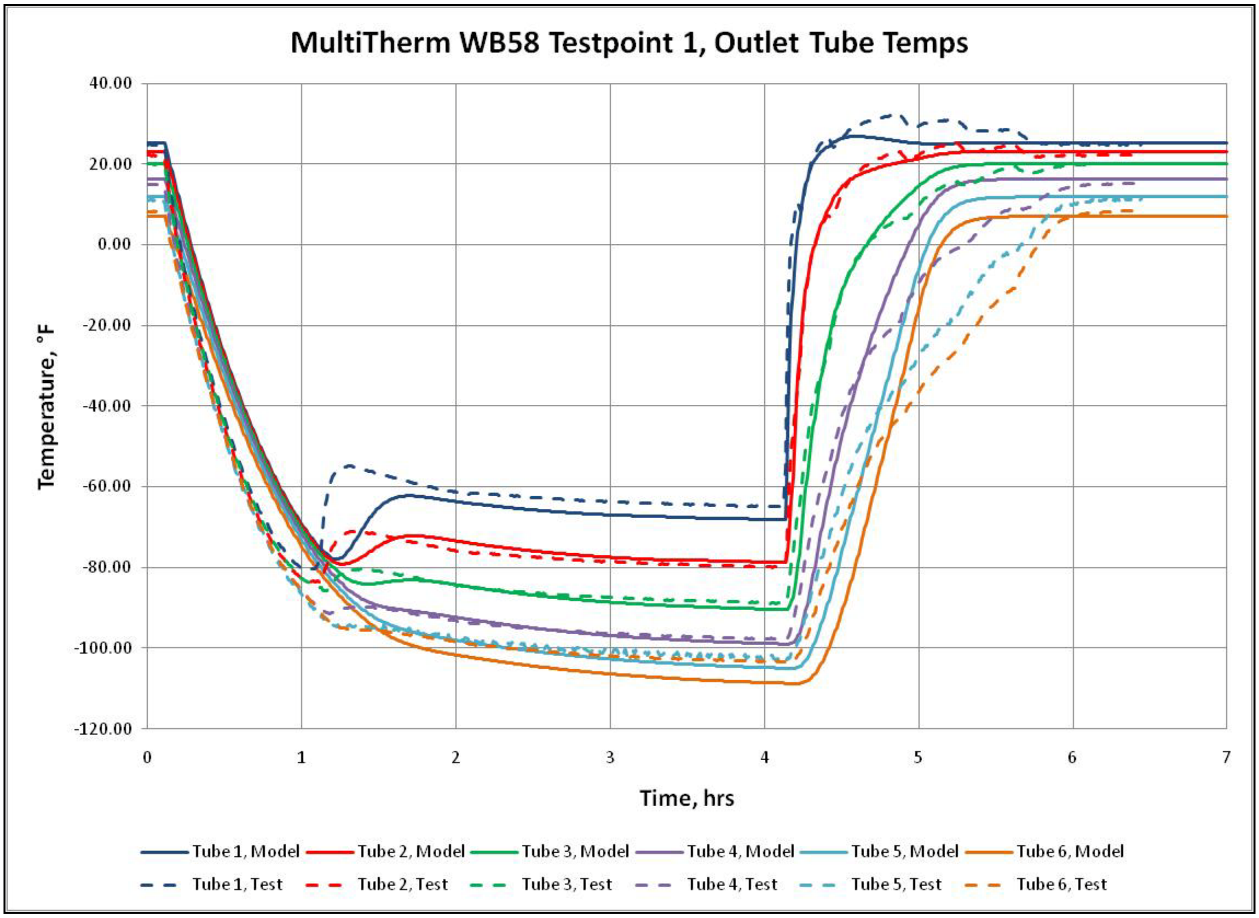

Figure 4: MultiTherm WB-58 freeze-thaw cycle. Tube outlet temperatures are shown in dashed lines, and model representations are shown in solid lines.

Amsoil ANT 50/50 with DI H_2O

Figure 5 shows the same data set as Figure 4, but for Amsoil ANT. The empirical data for tube six should be disregarded, as the thermocouple was malfunctioning. The model predicts freezing transients again very well, and again is off by approximately 30 minutes in recovery. Again the "notching" is seen as the tubes recover. Maximal heat rejection was 269 Watts at 31 lb/hr and 20°C. Minimal heat rejection was 130 Watts at 7.5 lb/hr and 20°C, making a turndown ratio of about 2:1.

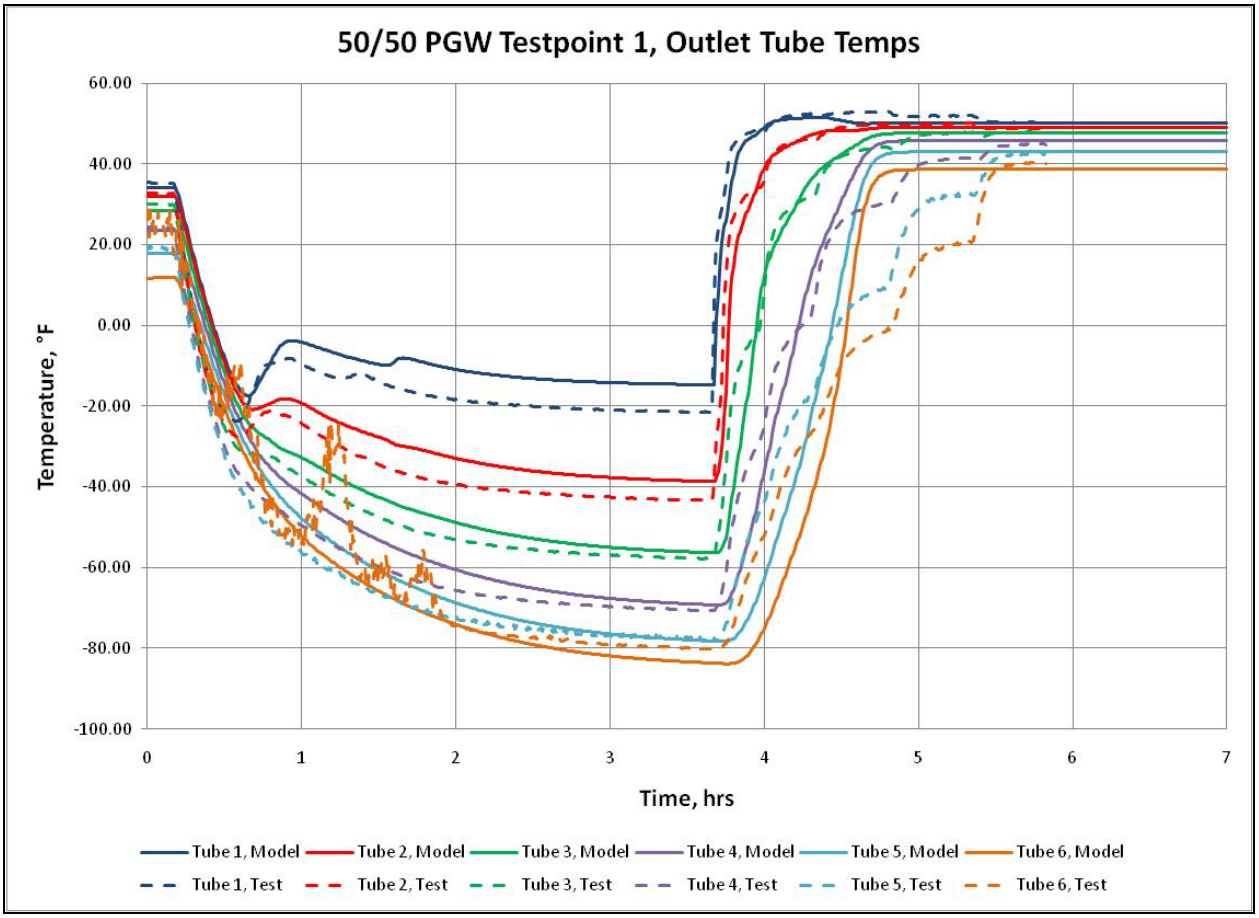

Figure 5: 50/50 Amsoil ANT/H_2O freeze-thaw cycle.

VI. DISCUSSION

While the transient predictions are not an exact match between the empirical data and the model, it should be noted that the test article did have some difficulties in that the heating lines adhered to the radiator as a backup in case total freeze occurred became delaminated. This creates an uncertainty in the radiator mass, as some undetermined amount of heating line was still adhered to the radiator panel. This uncertainty in mass can affect the rate at which temperature changes occur. In the empirical case, it would be expected that the radiator would respond faster than expected because, with the heating lines detached, the test article would be lighter than expected. This is one possible explanation for the faster freeze behavior shown by the test article in Figure 4.

While the fluid thermophysical properties appear to be very close, as shown by the good correlation with the test article in steady state temperatures, the nature of the thaw behavior appears to have nuances that are not yet incorporated into the model. The “notching” explained in the results section is not exhibited by the radiator model, though a general temperature overshoot of tube 1 is captured very well. It is possible that accurately capturing the way in which a solid slug of frozen fluid gradually thaws and then is pushed from the radiator tube before fully thawed may improve the recovery prediction of the model.

It should be noted that the model predicted heat rejection and turn-down ratio of the radiators exceptionally well, being within the error of instrumentation (2-5%) at both maximal rejection and minimal rejection for both fluids.

VII. CONCLUSION

From the results of this test, the opportunity arises to model some of the finer physical phenomena occurring during the thaw of a freezable radiator. Once these behaviors are captured in the model, it is reasonable to continue to a full scale design, incorporating four parallel radiators similar to the one tested here. Upon the successful completion of those objectives, an analysis should be carried out to ensure that the freezable radiator model scales well when taken away from its nominal dimensions, continuing to predict the behavior of radiators well. With these steps successfully in place, it can be confidently concluded that it is possible to predict the behavior of a freezable radiator for flight design.

REFERENCES TBD.

- CTSD-ADV-953